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THE DESIGN, OPERATION, AND USES OF THE WATER CHANNEL AS AN INSTRUMENT FOR THE INVESTIGATION OF COMPRESSIBLE-FLOW PHENOMENA

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SUMMARY

The results of several years' experience in the operation of a small water channel have shown that the hydraulic analogy can be used successfully to demonstrate many two-dimensional compressible-flow phenomena. Attempts to use the 20-inch-wide water channel at the Langley Laboratory for research projects, however, led to difficulty in the interpretation of the data with respect to practical flight problems because of the low value of the Reynolds number in the water channel. A channel permitting Reynolds numbers as large as 3,000,000 at tunnel choking would have to be approximately 10 feet wide if the water temperature were 200° F or 20 feet wide if the water temperature were 100° F.

The problem of maintaining a stable stream velocity has been solved by using a weir to control the total head and a variable-width Laval nozzle to control the mass flow through the channel. This system was capable of holding the stream velocity constant within one-half of 1 percent for an indefinite period.

The water channel is recommended as an effective low-cost demonstration instrument for use in the teaching of aerodynamic compressible flow and as an instrument for quickly checking new ideas.

INTRODUCTION

The application of the hydraulic analogy to the investigation of compressible-flow phenomena has previously been discussed in reference 1. Since the publication of that paper, a number of modifications have been made on the water channel in operation at the Langley 8-foot high-speed tunnel which have definitely increased the ease of operation of the channel and the accuracy of the data obtained therefrom. The principles involved in these changes are presented along with a number of suggestions concerning the design of such a channel and its uses.

The auxiliary apparatus, such as depth-survey systems, stream-velocity controls, manometers, and equipment for flow observation by optical methods, is considered in detail because the more important advances in the water channel have been improvements in the auxiliary apparatus. Suggestions are also included that concern the operation of a water channel, the adjustment of the test-section floor shape in order to obtain a flow in the test section free from velocity gradients, the computation of data, and precautions necessary for proper interpretation of the data obtained.

SYMBOLS

a	velocity of sound
d	height of water surface above floor at test-section entrance
d_o	stagnation depth of water
g	acceleration due to gravity
l	chord of model
M	Mach number
p	local pressure
p_o	stagnation pressure
R	radius of curvature of surface
R_n	Reynolds number
T	local temperature
T_o	stagnation temperature
V	velocity of water
W	width of channel
γ	ratio of specific heat at constant pressure to specific heat at constant volume
θ	slope of water surface

μ viscosity of water

ρ density of fluid

ρ_o stagnation density

DISCUSSION OF THE HYDRAULIC ANALOGY

Nature of the Analogy

A theoretical discussion of the analogy between the flow of water with a free surface and the two-dimensional flow of a compressible gas is presented in reference 2.

The following table taken from reference 1 presents the analogous relationships derived from a consideration of the energy, continuity, and potential equations of the two types of flow:

Significant quantities and characteristics of two-dimensional compressible gas flow, $\gamma = 2$	Corresponding values in analogous liquid flow
Temperature ratio T/T_o	Water-depth ratio d/d_o
Density ratio ρ/ρ_o	Water-depth ratio d/d_o
Pressure ratio p/p_o	Square of water-depth ratio $(d/d_o)^2$
Velocity of sound $a = \sqrt{\frac{\gamma p}{\rho}}$	Wave velocity $\sqrt{gd}$ 1.64 f/s
Mach number V/a	Mach number $V/\sqrt{gd}$
Subsonic flow	Streaming water V = .67 fps
Supersonic flow	Shooting water
Shock wave	Hydraulic jump

Inasmuch as the analogous relationships depend upon the depth of the water and no other variable remains to represent a third dimension, the hydraulic analogy is strictly limited to two-dimensional phenomena.

Uses of the Hydraulic Analogy

A unique feature of the hydraulic analogy is the possibility of obtaining undisturbed measurements in the flow field about a two-dimensional profile shape. This feature is of value for the study of various phenomena such as the interference of the tunnel walls on the flow about models or the study of shock phenomena in supersonic flow fields. The channel is also useful for the demonstration of many compressible wind-tunnel phenomena such as choking in subsonic wind tunnels, schlieren and shadowgraph principles, and flow in a supersonic nozzle.

WATER-CHANNEL DESIGN

The design of a water channel is somewhat similar to that of a wind tunnel. (See fig. 1(a).) The water flows from a large quieting section through a converging entrance section, where it is accelerated, into a constant-velocity test section where the model is placed; finally, a pump or propeller returns the water to the quieting section. The channel shown in figure 1(a) is the vertical-return type and is considered more satisfactory than the horizontal-return type shown in figure 1(b) because less space is required and the water surface is not disturbed with turning vanes. The horizontal design (fig. 1(b)) would probably be more satisfactory for large installations because most of the channel could be supported directly on the ground and could be built of concrete.

Entrance Sections

Two types of entrance sections are shown in figure 2, each of which may be used with either type of channel. The vertical entrance section (fig. 2(a)) has the same width as the test section and constricts the water flow by changing the depth of the channel. In order to avoid waves in the test-section and to assure a uniform velocity distribution throughout the depth of the water, the final approach of the entrance floor to the test section should be very gradual.

The horizontal entrance section (fig. 2(b)) has a level floor in the plane of the test section. The analogy applies to this entrance section as well as to the test section and, as a result, the principles of design of two-dimensional wind-tunnel entrance cones may be applied. The wide settling basin required for this entrance section makes the channel more expensive because of greater space and material requirements. Some difficulty was experienced with the use of this type of entrance because of secondary flow at the vertical walls, such as described in reference 3.

Test Sections

The walls of the channel through which the water flows must be perpendicular to the surface of the water and the floor over which the water flows must be a horizontal plane in order that the pressure of the fluid at any point may depend only on the height of the free surface at that point. The condition on the walls may be included in the design, but the floor must be modified because of the growth of the boundary layer. Thus, the effective rather than the physical floor should be plane and horizontal. The floor, therefore, must be designed so that its shape can be adjusted. A suggested method is shown in figure 2(a) in which the test-section floor is supported on blocks, the height of which may be varied by using shims, or on a set of screws placed through the lower floor. The greater versatility of the screws is not necessary for subsonic test sections, as the floor setting need not be changed once satisfactory flow is attained.

If visual observation methods are to be used, glass plates are required in both floors for the transmission of light through the water.

Circulating Systems

The pump used for the circulation of the water should be designed for a pressure increase of two to five times the total depth of the water plus the losses in the antiturbulence screen. The maximum volume of flow must be equal to the amount required to choke the tunnel. A marine propeller is considered the best suited for this purpose, as it can pump a large volume of water at a low pressure and with a minimum increase in the turbulence level of the water. Several types of installation may be used. The arrangement shown in figure 1(a) does not require that a packing gland be kept watertight as would be the case if the drive shaft passed through the tunnel wall.

Construction Materials

Experience with the channel in operation at the Langley 8-foot high-speed tunnel has shown that the most important maintenance problems are caused by the formation of rust and the growth of algae. The algae may be inhibited by using a small amount of copper sulphate in the water. The use of steel has proven unsatisfactory since it promotes the formation of rust and the presence of iron causes the copper to precipitate out of the solution, thereby rendering it ineffective against the algae. It is therefore desirable to use some other material which does not possess the characteristics attributed to the iron.

MODEL DESIGN

Models are restricted to two-dimensional sections with the axis perpendicular to the water surface. A sketch of airfoil-type models is shown in figure 3. The pressure orifices should be flush with the surface and have small openings located near the bottom of the model. For reasons to be discussed later, the model shown in figure 3(b), which has pressure manometer tubes within the model, may prove convenient. Because of the space required for the tubes, this type model could be used only in a large channel. The material of which the models are made must be unaffected by the water.

AUXILIARY EQUIPMENT

Depth-Survey Systems

Because surveys of the depth of the water in the test section are required, a system is necessary which permits measurement of the depth of the water at any point over the test section. Such a system is shown in figure 4 in which a depth gage is mounted on two sets of rails in such a manner that it may be moved to any point over the test section. The tolerances in design and construction of the cross-rail system should permit measuring the depth of the water to one part in a thousand.

The system may be designed for hand operation of the depth gage if the channel is less than 40 inches wide. If the channel is over 40 inches wide, remote control of the survey system is desirable. The possibility of mounting several depth gages on the cross rails could be considered for reducing the time required to take surveys in a large channel.

The depth gage should have an indicating system which is sensitive to about 0.0005 of the total depth of the channel. The range of the indicating system should cover the distance between the floor of the channel and the total depth of the water. If a gage is not available which will cover the entire range, different length probes may be used to extend the range. The probes should have noncorrosive tips, preferably platinum.

An electronic relay which indicates contact of the probe and the water surface is very convenient and is required when the capillary conditions or other flow conditions render a visual observation of the contact of the probe with the water surface almost impossible. Because the relay is connected between the probe and the water, the probe must be insulated from the frame of the supporting carriage.

Velocity-Control Equipment

Subsonic velocities of the water may be controlled by use of a variable-speed motor to drive the propeller. The speed-control requirements on such a motor are, however, quite rigorous. In order to set the channel at Mach numbers near 1, the motor speed must be variable by increments of one part in a thousand and must remain constant within one part in a thousand. Even if the motor speed control meets these rigid specifications, the stream Mach number varies over a period of time because evaporation and leakage losses change the total depth of the water and changes of resistance in the antiturbulence screen due to collection of rust and algae change the pressure drop available to force the water through the test section.

In order to eliminate these problems, another system of velocity control was devised for and used in the water channel at the Langley 8-foot high-speed tunnel. This system consists of two parts; one controls the total head, and the other controls the mass flow for any given total head.

The total head is held constant by replacing a long, level, overflow weir across the settling basin. (See fig. 5(a).) The flow over the weir is drained into an open outside tank and then pumped back into the channel with a constant-volume pump. The fact that this system will maintain the total head at a constant value may be seen by examining the flow conditions. Suppose that a change occurs during the operation of the channel which will cause the total depth to increase; then more water will flow over the weir than is returned by the pump and, as a result, the total depth will decrease to its original value. Likewise, if the total depth decreases, less water will flow over the weir than is returned by the pump and, thereby, the total depth is increased to its original value.

The stream velocity was controlled by placing a Laval nozzle of adjustable width in the channel downstream of the test section. (See fig. 5(b).) The back pressure downstream from the nozzle was held low enough to choke the flow through the nozzle. By changing the width of the nozzle, the mass flow through it and, consequently, the mass flow through the test section could be controlled very readily and, thus, an excellent and stable control of the stream velocity and Mach number is provided.

The entire velocity-control system proved to be very satisfactory. For example, several floor boundary-layer tests were made which required that the channel operate at a stream Mach number of 0.980 for a period of 8 hours. This control system held the Mach number of the channel within one-half of 1 percent of that value for the entire period with no changes in adjustment, an achievement which is practically impossible to attain by means of a variable-speed drive-motor system.

An alternate method of stream-velocity control is suggested in figure 5(c). This method uses the flow over a weir of adjustable height, rather than the variable-width Laval nozzle, as a control of the mass flow through the channel. This method has not been used in the Langley channel but should be equally successful. Either method requires very sensitive means of adjustment if adequate control of stream Mach numbers near 1.0 is desired.

Manometers

The water depths close to a wall cannot be read with a depth gage because the capillary attraction of the wall for the water surface raises the local height of the water level; hence, the water depths at a wall or model surface must be read by means of pressure orifices connected to tubes in a manometer. The design of several manometers used in the Langley channel is shown in figure 6. Inasmuch as the water-depth increments which are to be measured are quite small, the tubes must be slanted as in figure 6(a) to magnify the readings, or a micrometer depth gage must be used to read the depths as in figure 6(b).

The slant-tube board is easier and faster to read than the vertical-tube board but is less accurate because of the greater effects of the capillary attraction of the tube for the water surface. The vertical-tube system is recommended where accurate results are required. This system is more accurate because the depth gage can be read more closely and because the capillary attraction of the larger tubes is much smaller so that the inherent error of the system is reduced. The tubes in either system must be kept clean so that the capillary attractions will be uniform for all the tubes and can be eliminated in the calibration of the manometer.

Streamline Systems

A streamline system is convenient for the study of streamline patterns, tunnel turbulence, separation, wakes, and other phenomena. Hypodermic syringes with needles having the points ground off and the ends bent through a 90° turn have been used with fair success. A methlyene-blue dye solution was used to indicate the streamline.

Shadowgraph and Schlieren Systems

Because the slope of the water surface will bend light just as does a density gradient in air, the same optical methods may be used for visual observation of the flow. Although the same principles are used, the operational characteristics of the systems used with the channel can be expected to be different because of the greater bending of the light. The light path through the water may be bent 10° or more, whereas in air the maximum bending is of the order of 1' or 2' or less. Thus, the requirements on optical systems for the water channel will be much less severe than those for air. In fact, the schlieren system presents the problem of reducing its sensitivity to such an extent that the range of contrast found in the image will be representative of the entire range of slopes of the water surface. Usually, shadowgraph systems are employed instead of schlieren systems because of their simplicity and lower sensitivity.

The optical parts of the shadowgraph system used in the Langley channel are shown in figure 7. The only equipment required is a point light source, optical condenser, mirror, ground-glass screen, and camera. None of the components are critical. An arc lamp, automobile headlight bulb, or any other brilliant point source may be used as the light source. The camera should be capable of taking a good exposure at 0.005 second in order to prevent blurred pictures of unstable phenomena. Several examples of shadowgraphs may be observed in the figures of reference 1.

The addition of schlieren equipment to a channel would be excellent for demonstrating the mechanics of a schlieren system but, for the reasons previously discussed, might not be satisfactory for flow observation. The requirements of a water-channel schlieren system are opposite to those of an air system. In order to reduce the sensitivity, the focal lengths must be as short as possible and the stop openings much larger than those used for air. These requirements suggest the use of lenses with f 2 to f 3 aperture ratings and stop dimensions equal to 10 to 20 percent of the focal length of the lenses. The arrangement shown in figure 8 was tried and not considered satisfactory because the optical condensers would not form a fair image of the airfoil and because the image was brilliantly illuminated along the lines of zero slope of the water surface and dark over the remainder of the image, so that an interpretation of the entire field is prevented.

ADJUSTMENT AND OPERATION TECHNIQUE

Calibrations and Maintenance

In order to obtain accurate data, both the measuring instruments and the channel test section must be carefully calibrated and maintained. The depth gage should be checked by measuring the height of a calibrated gage block set at a definite reference point on the test-section floor, for example, the center of the model location. Then the channel should be filled to approximately the height of the gage block, and a survey of the depth of the static water should be made to check the accuracy of the depth-survey system. If the depth gage readings over the entire test section are not equal to the reading at the reference point, the increments between the reference-point reading and the readings at the local points should be calculated and used as corrections to the local readings to obtain the true depths of the water. The same process should also be used for each manometer except that, instead of referring to a gage block, a known depth of water in the channel as determined by the previously calibrated depth-survey system may be used as the standard reference point. Field-survey plots of the calibration increments facilitate the correction of data.

Experience has shown that all calibrations are sensitive to differential expansions caused by changes in the temperature of the room in which the channel is located. This problem was met by keeping the temperature constant within $\pm 3^{\circ}$ F.

The regular maintenance of the channel should include cleaning the antiturbulence screens daily, or oftener if needed, keeping the floors and walls free from rust, algae, and other surface-roughening conditions, and occasionally checking the various calibrations. The calibrations of the depth-survey system may be expected to be quite stable; whereas the calibration of the manometers requires checking at frequent intervals.

Adjustment of Test-Section Floor Shape to Obtain Uniform Flow

After a channel is in operation, a survey of the velocity distributions through the test section will probably show that the velocity is nonuniform. The nonuniform condition may be removed by properly adjusting the shape of the test-section floor. As a first trial, the shape of the floor should be set to compensate for a boundary layer calculated from considerations of the flow along a flat plate. (See reference 4.) This setting should be checked by operating the channel at a Mach number of 0.95 to 0.98 at the model location. This Mach number range is chosen because it represents a range in which the flow is extremely sensitive to the effects of the floor boundary layer. Experience has shown that flow free from velocity gradients at stream Mach numbers in the neighborhood of 0.95 are free from velocity gradients at lower stream Mach numbers.

After the velocity distribution of the adjusted floor is examined, small nonuniformities may remain. These nonuniformities may be removed by raising the floor slightly at low velocity points and lowering the floor slightly at high points. The floor should be level in the direction transverse to the flow. It will be observed that progressively lowering the downstream pressure below the value required to choke the test section progressively increases the stream Mach numbers to values slightly greater than 1. The attainment of supersonic flow is attributed to a thinning of the floor boundary layer downstream of the throat.

Suggested Nomographs for the Calculation of Data

Reference 1 shows that the Mach number of the flow may be calculated by the formula

$$M = \sqrt{\frac{2(d_o - d)}{d}}$$

This formula may be plotted as shown in figure 9(a), in which each line represents one Mach number and is a straight line through the point (0,0). Such a graph is recommended to facilitate the computation of Mach numbers.

A similar graph may also be made up for velocities. The formula for velocity $V = \sqrt{2g(d_o - d)}$ is shown as a nomograph in figure 9(b). This chart is convenient for the computation of velocity ratios, increments, and other functions pertaining to velocity.

CHANNELS FOR RESEARCH

The width of a channel which is to be used for research may be obtained from a consideration of the Reynolds number of the flow about a model at the tunnel choking condition. The Reynolds number of the flow about a model, when the model is assumed to be completely submerged, may be expressed by the formula

$$R_n = \frac{\rho l V}{\mu} \tag{1}$$

where

$$V = \sqrt{2g(d_o - d)} \tag{2}$$

This formula may be used to compute the channel width required to obtain a given Reynolds number at choking if the ratio of the water depth to the channel width and the ratio of the model chord to the channel width are known. Experience with the Langley channel has shown that a fair compromise is obtained between vertical-acceleration effects and floor boundary-layer effects if the total depth of the water is one-sixteenth of the width of the channel. If reasonably small wall interference effects are to be obtained, the chord of a slender model should not be over one-fourth of the channel width. By substituting the choking velocity for V (reference 1) and letting $d_o = \frac{W}{16}$ and $l = \frac{W}{4}$

$$R_n = \frac{\rho \frac{W}{4} \sqrt{\frac{2g}{3} \frac{W}{16}}}{\mu} \tag{3}$$

$$R_n = 26,520W^{3/2} \tag{4}$$

where W is expressed in feet, $\rho = 1.941$ slugs per cubic foot, $\mu = 0.00002111$ slug per foot second at 68° F, and $g = 32.2$ feet per second per second.

By solving equation (4) for W, it may be shown that a channel capable of tests at an assumed model Reynolds number R_n of 3,000,000 should be 23.4 feet wide. The channel size may be appreciably reduced by heating the water. At 208° F, $\mu = 0.00000607$ slug per foot second, and equation (4) becomes

$$R_n = 88,800W^{3/2} \tag{5}$$

The channel width at the elevated temperature condition is thus reduced to 10.5 feet.

A channel that is to be used for research projects which require model Reynolds numbers as large as 3,000,000 should be a minimum of 10 to 20 feet wide and should include provisions for operating at elevated temperatures. Because the elevated temperatures will introduce new problems such as steam over the water, uncomfortable working conditions, and excessive heat losses, some compromise of the temperature and channel width is probably necessary.

Several of the disadvantages of the high water temperatures can be eliminated. The weir velocity-control system eliminates velocity changes due to evaporation losses. Insulating the entire channel would reduce the amount of heat required to keep the water at operating temperature, and keeping the channel covered except over the test section would reduce the danger to personnel. The manometer, which must be at the temperature of the water, could be built into the walls of the tunnel. If the model is large enough, the tubes can be mounted in the model and read with the depth-survey system as previously shown in figure 3. The most difficult problem would probably be the elimination of the steam over the test section and the design of a survey system which would not corrode in the humid atmosphere.

CHANNELS FOR DEMONSTRATION

Because many of the effects of compressibility may be shown at lower Reynolds numbers than are required for fairly accurate quantitative data, a water channel that is to be used for demonstration of compressible-flow phenomena may be much smaller than the suggested size of a research channel. The water channel used at the Langley 8-foot high-speed tunnel is 20 inches wide and has been satisfactory for demonstration purposes. Some of the results which have been obtained in this channel are given in reference 1. A demonstration channel could be somewhat wider than the Langley channel, although its test-section width probably should not exceed 40 inches because of the difficulty of operating the field-survey equipment over the center of the test section.

The channel which is to be used primarily for demonstration should be versatile; that is, rapid changes of models, nozzles, and stream velocities should be possible. If the weir velocity-control system is used, it should be supplemented with a variable-speed drive motor. The variable-speed drive motor is very useful for rapid visual observation of phenomena when the point of interest is the development of shocks in the flow or other changes in the field about the model.

The properties of the flow fields may be demonstrated either by visual means or by measuring the fields with a depth-survey system. The channel should be designed so that either system may be used. The use of visual observation methods requires that the floor be transparent and that sufficient space be allowed under the test section for the location of the required optical equipment. Although visual observation is convenient and rapid, many of the effects of compressibility cannot be visually observed and, as a result, must be demonstrated by surveys of the water surface. Thus, if a channel is to be useful for a variety of projects, an accurate depth-survey system must be incorporated in the design.

The uses of a channel as a demonstration instrument suggest that it would be a valuable low-cost piece of laboratory equipment to be used in conjunction with a course in the aerodynamics of compressible flows. Many experiments may be suggested which would help the student to gain an understanding of the problems met in high-speed wind-tunnel research technique. A few phenomena that can be demonstrated are: effects of compressibility on airfoil pressure distributions, streamline flow, wakes and flow separation, tunnel choking phenomena, subsonic and supersonic nozzles, and subsonic and supersonic flow about airfoil sections.

EVALUATION OF RESULTS OBTAINED FROM WATER CHANNELS

The limitations of the hydraulic analogy that must be considered in the analysis of data obtained from a water channel are:

(1) A value of the ratio of specific heats γ different from that obtained in air

(2) The requirement that the vertical acceleration be small with respect to the acceleration of gravity

(3) The appearance of waves other than the long gravity wave which corresponds to the sound wave in air

(4) The thick laminar boundary layers existing at the low Reynolds numbers characteristic of channels of practical size

The fact that γ is equal to 2 is not as serious a restriction on the analogy as might at first be expected. A discussion of the subject is presented in reference 1 in which it is shown that subsonic local Mach numbers are not seriously affected by changes in γ. It may be expected, though, that the errors due to the incorrect value of γ will become more serious when the stream Mach numbers become much greater than 1.0.

The severity of the effects of vertical acceleration of the water depends upon both the slope θ of the water surface and the ratio of the depth of the water d to the radius of curvature R of the surface. So long as both θ and d/R are small the vertical acceleration will be small compared to the acceleration of gravity. When either θ or d/R or both become large, for example, near stagnation points on sharp-nose airfoils, near pressure peaks, and within shocks, the vertical acceleration is an appreciable part of the acceleration of gravity, and hence may seriously affect the results. The effect of appreciable vertical accelerations is to give an absolute value of the slope of the water surface different from the absolute value required to represent correct compressible-flow conditions. Thus, the water will not reach stagnation depths except for very blunt models, the full value of the pressure peaks will not be attained, and shocks will be diffused into broad bands. In fact, hydraulic jumps which are analogous to shock waves are not readily observable unless they are normal and stream Mach number is 1.5 or larger.

The effects of the capillary waves are a serious handicap to shadowgraph observation because the waves are more prominent in the photographs than are many of the phenomena which the observer is studying. An analysis of shadowgraphs thus requires particular care in distinguishing between capillary waves and analogy phenomena; however, when the observations are recorded and plotted as depth surveys, the capillary waves usually appear as short sinusoidal waves with somewhat smaller amplitudes than the analogy phenomena and may easily be faired out of the final results. Field surveys may thus be plotted for analyses which are relatively unaffected by capillary phenomena.

Several attempts have been made to reduce the capillary effects by adding wetting agents to the water. The results showed fewer waves originating at the walls and model because the wetting was more uniform; however, unstable shocks, such as those found in the mixed-flow region, create disturbances which cause capillary waves so that the benefits gained by the use of the agent were nullified.

The effects of the floor, wall, and model boundary layers on the experimental results must also be considered in the analysis. The effects of the floor boundary layer are the most serious, because this boundary layer represents an appreciable percentage of the entire flow. One effect of the floor boundary layer has already been mentioned, that is, the attainment of low-supersonic stream Mach numbers. Other observations have shown that subsonic wall interference effects are reduced and the choking Mach number appreciably increased because of floor boundary-layer effects. Thus, when results are obtained which are not in accord with wind-tunnel experience, the effects of the floor boundary layer should be analyzed for a possible explanation. The boundary layer on small models causes separated flow which produces pressure distributions different from those obtained if the flow does not separate. The effects of the wall boundary layer are not serious, as it represents but a small percentage of the total mass flow and is located some distance away from the model.

It is because of the serious effects of the boundary layer that the suggestion was made that any channel primarily intended for research should have as large a Reynolds number as possible. At the suggested Reynolds number of 3,000,000, separation phenomena at the model should be similar to comparable phenomena found in a 2-foot-diameter wind tunnel; whereas the 20-inch-wide demonstration channel is comparable to a wind tunnel about 0.4 inch in diameter.

CONCLUDING REMARKS

Although the inherent limitations of the hydraulic analogy tend to restrict the accuracy of the pressure distribution about a model, the water channel is nevertheless a valuable instrument for the study of two-dimensional compressible flow. The significant flow quantities are easily measured in the field about the model. The most serious restrictions imposed by the low Reynolds number may be overcome by building a channel at least 10 to 20 feet wide and by heating the water to 100° F or more.

Even a small, low Reynolds number channel that is quickly constructed and is economical both to build and to operate may be of appreciable value for the demonstration of compressibility phenomena. These demonstrations should be especially valuable to the student who is studying compressible aerodynamics because of the many concepts which he may obtain from the operation of the channel and the analysis of the results of the water-channel experiments. The channel is quite valuable for the purpose of quickly checking new ideas and also as a guide to the correct approach in a wind-tunnel investigation.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
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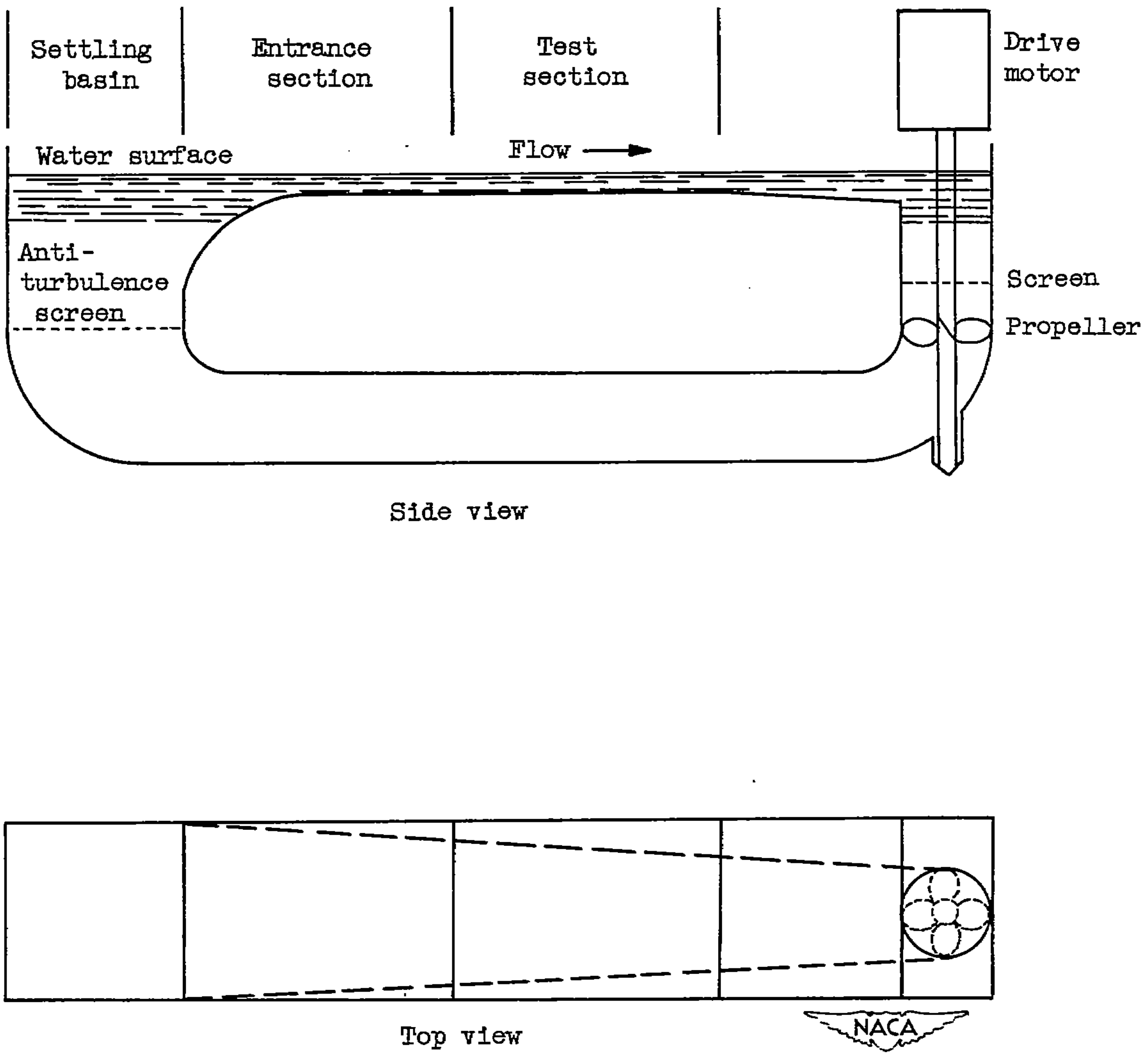
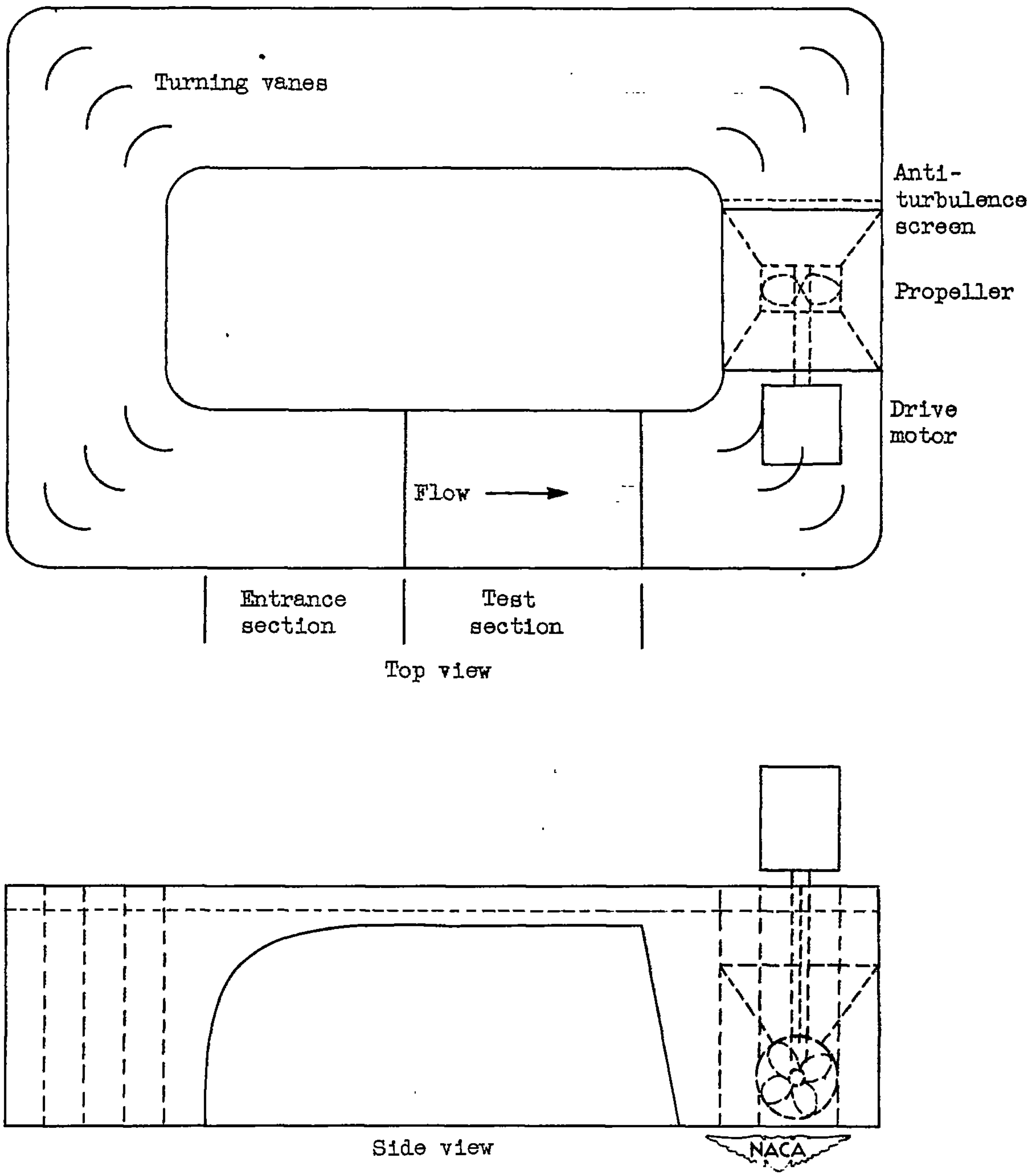


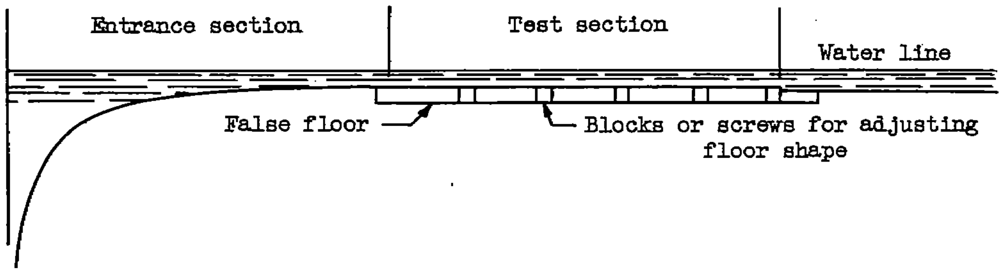
(a) Vertical return channel.

Figure 1.– Two types of water channels.

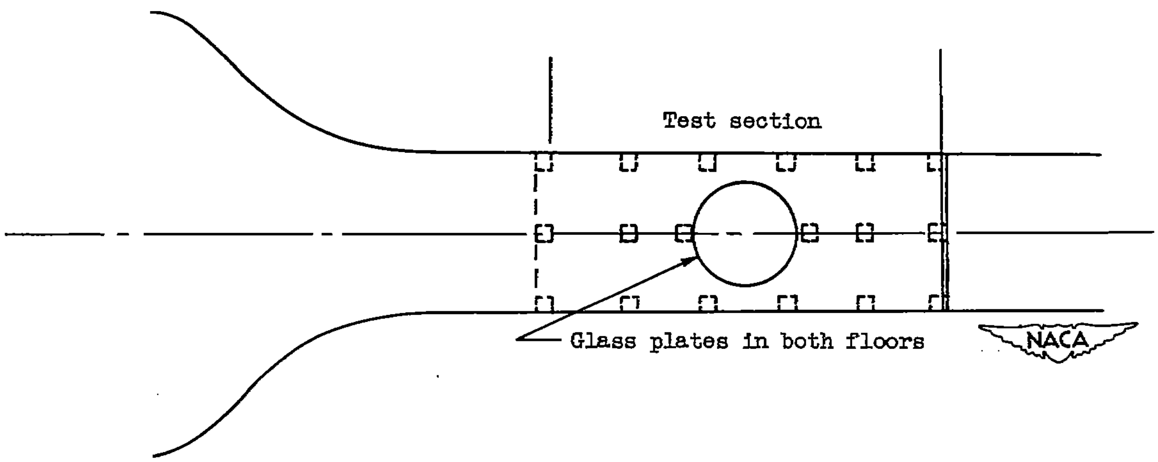


(b) Horizontal return channel.

Figure 1.— Concluded.

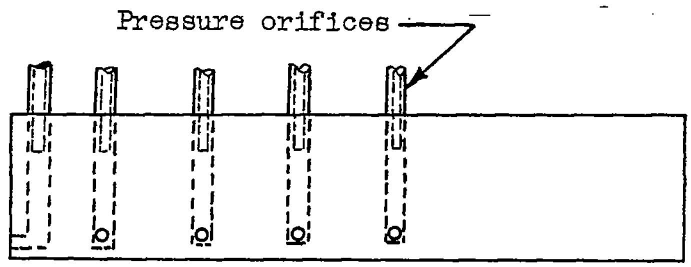


(a) Vertical entrance section and test section.

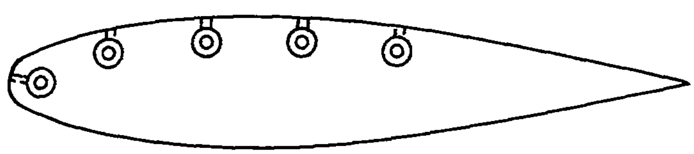


(b) Horizontal entrance section.

Figure 2.– Entrance and test sections.

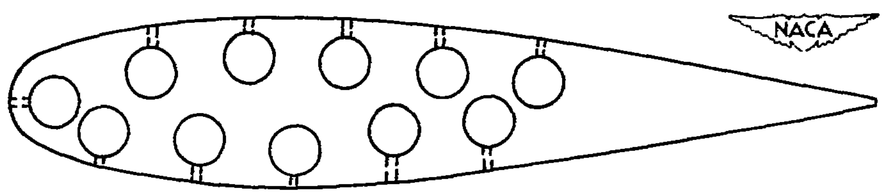


Side view.



Top view.

(a) Small model with pressure orifices connecting to an external manometer.



(b) Large model with manometer tubes installed within model.

Figure 3.— Models for a water channel.

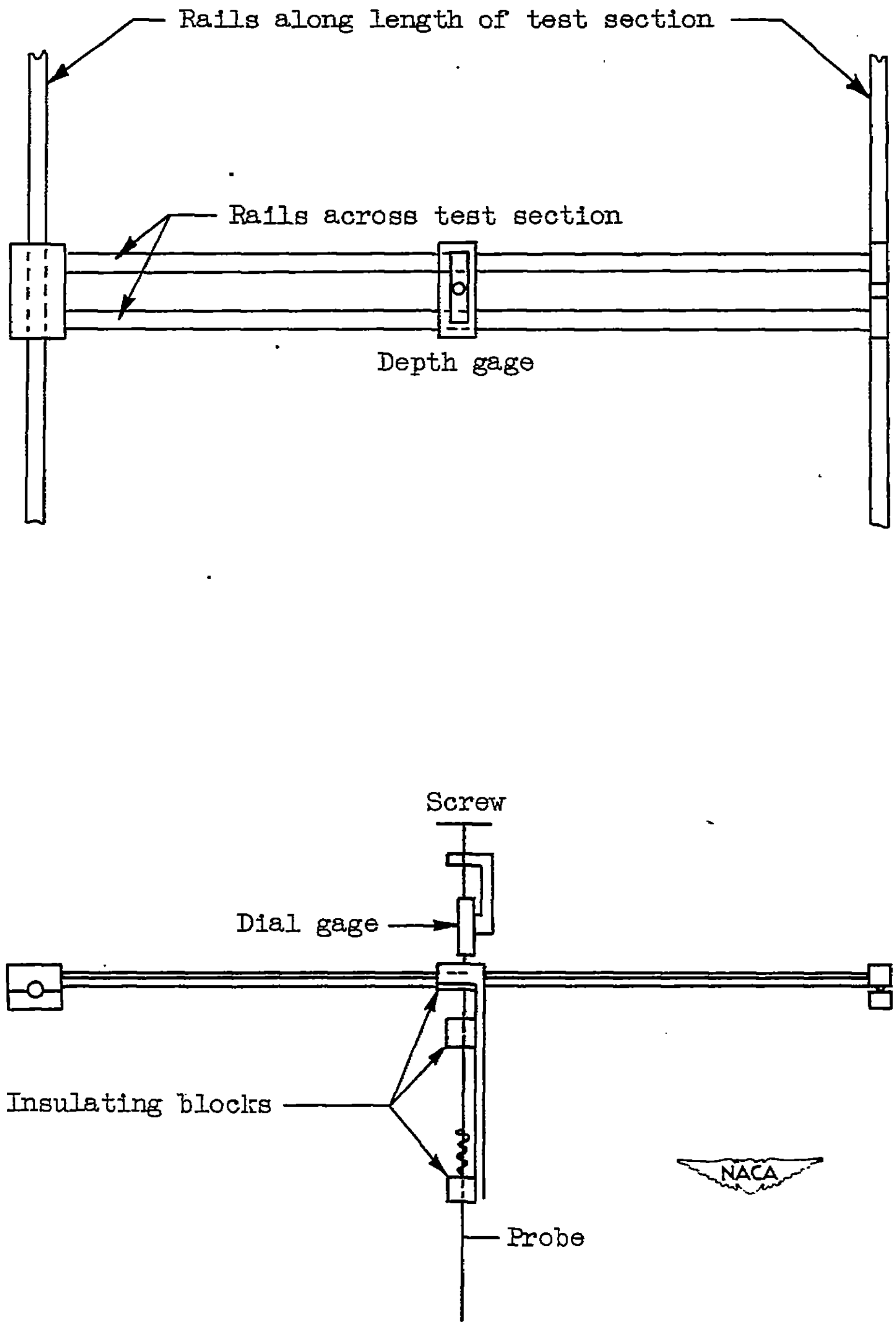
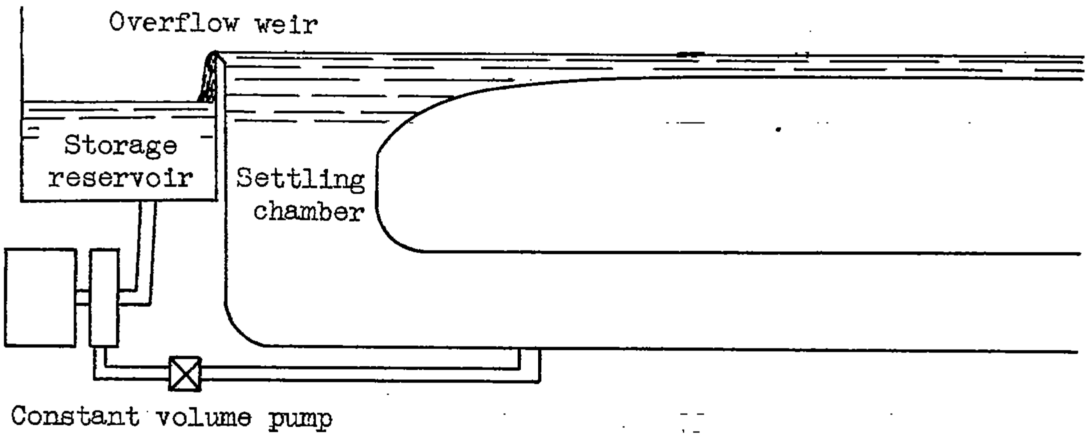
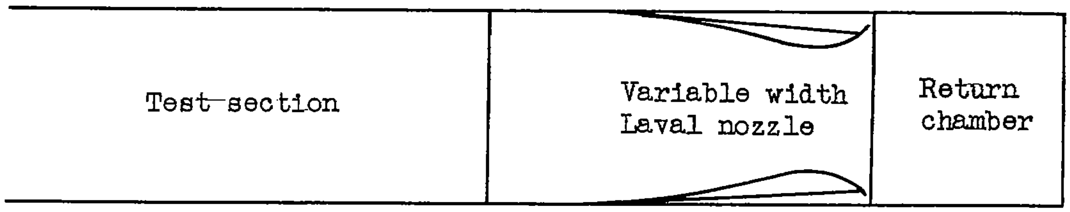


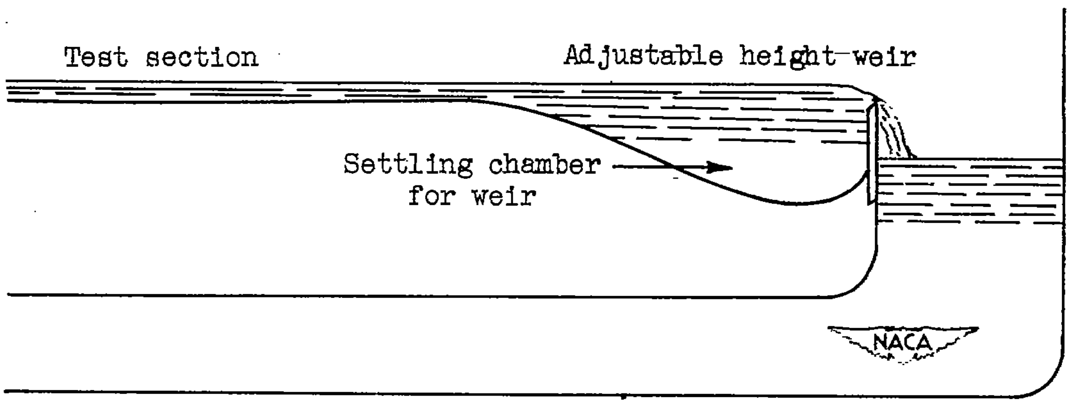
Figure 4.– Depth survey systems.



(a) Constant-total-head control system.

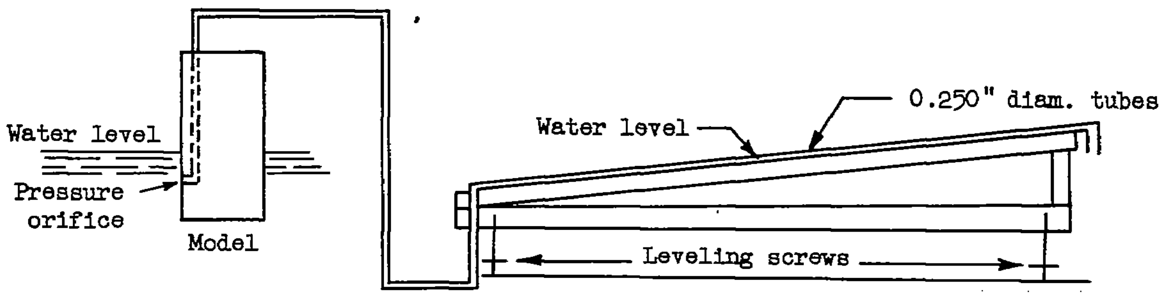


(b) Laval nozzle stream-velocity control system.

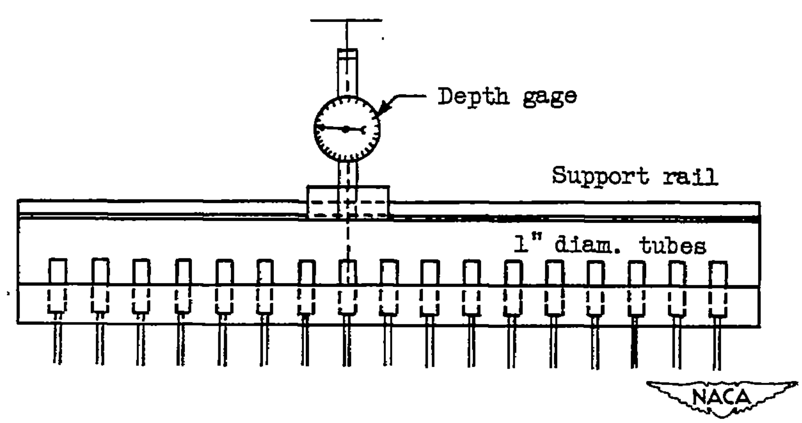


(c) Weir stream-velocity control systems.

Figure 5.– Suggested water channel stream-velocity control systems.



(a) Slant-tube manometer board.



(b) Vertical-tube manometer board.

Figure 6.– Manometer systems.

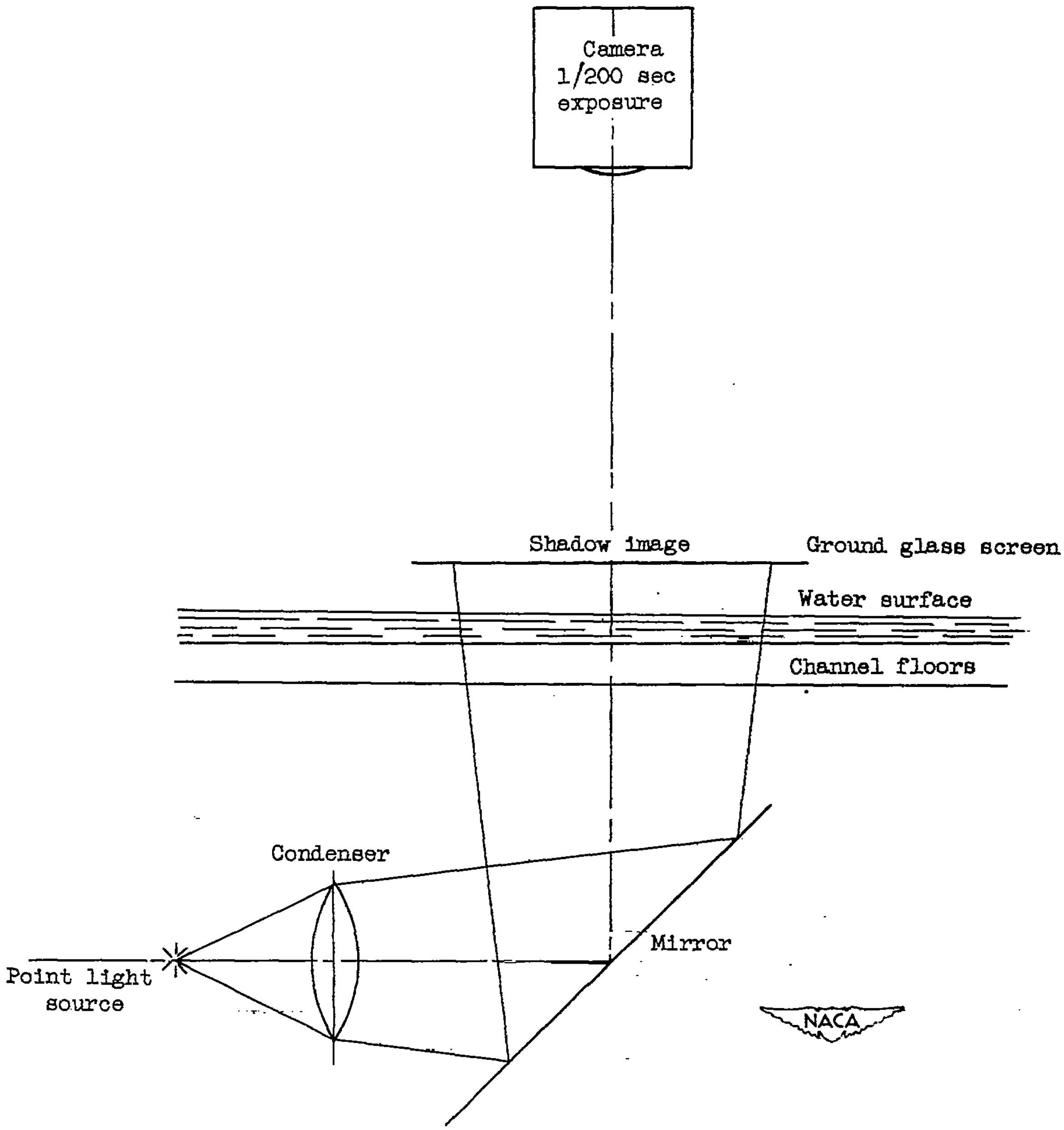


Figure 7.- Typical shadowgraph system.

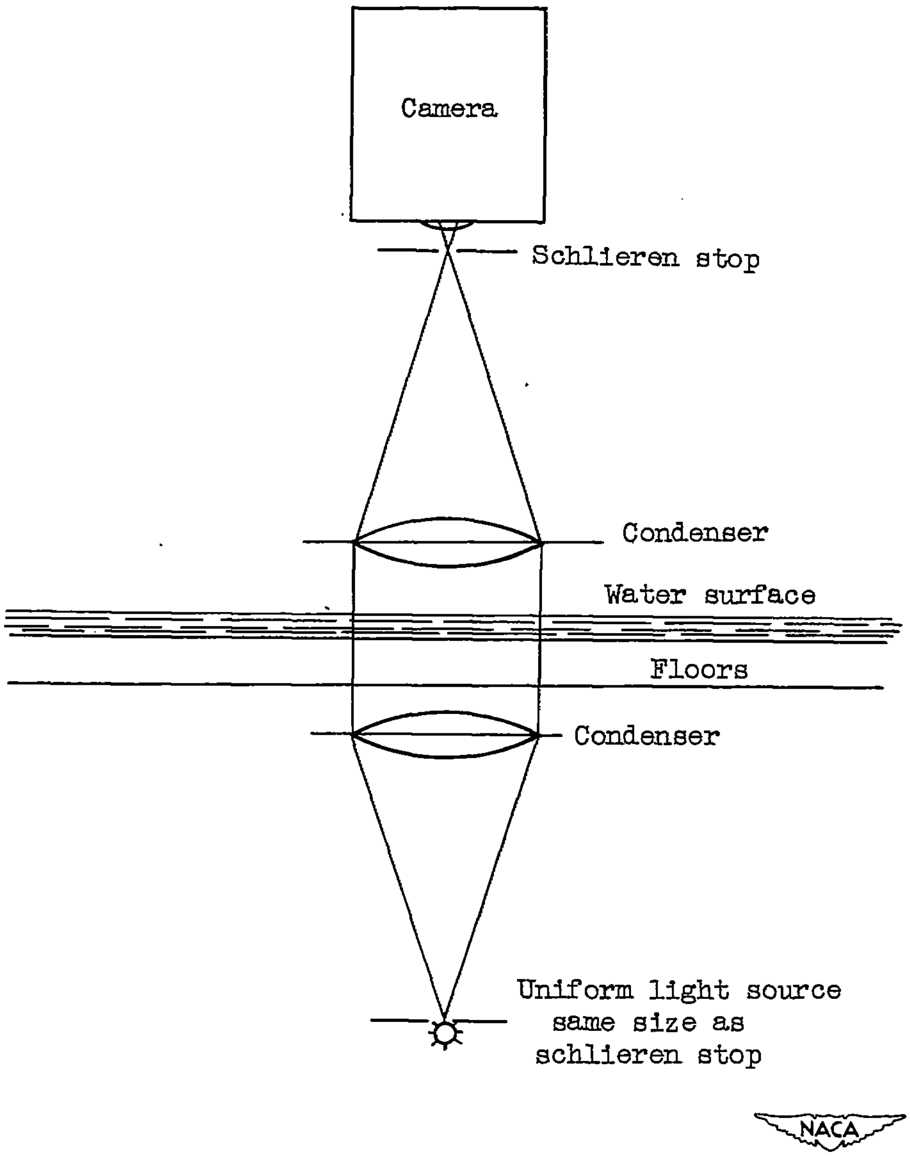


Figure 8.– Demonstration schlieren system for water channels.

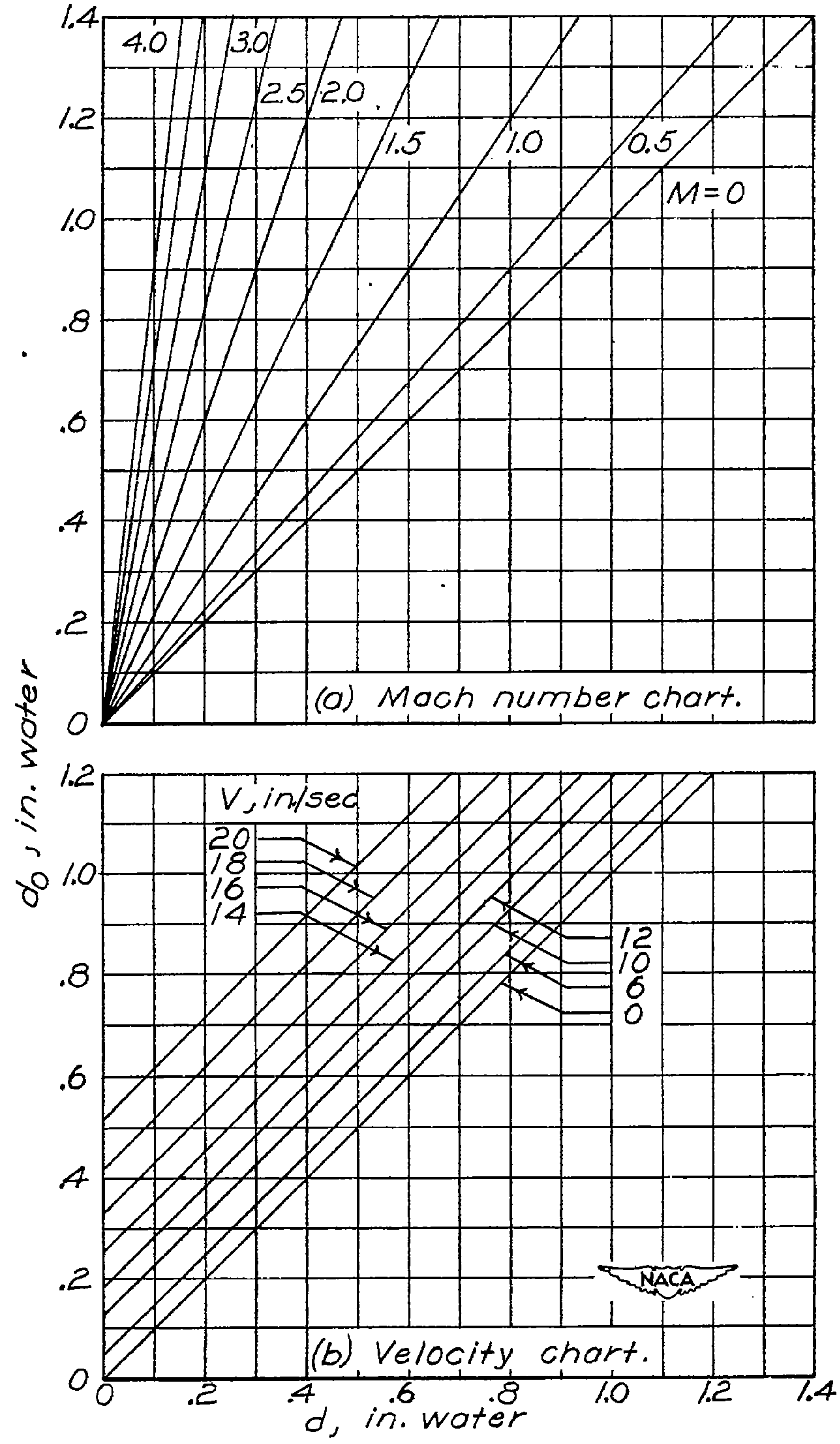


Figure 9.– Charts for computing water-channel data. $M = \sqrt{2\frac{(d_o - d)}{d}}$;

$$V = \sqrt{2g(d_o - d)}.$$

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